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Materials availability for thin film (TF) PV technologies development: A real concern?

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ABSTRACT

Decarbonisation goals have triggered photovoltaic (PV) sector expansion and cost reductions in PV technologies. Thin film (TF) PV technologies are currently the cheapest to manufacture and offer the possibility of attaining lower costs. However, scarcity of key component materials has been highlighted as a potential barrier to both large scale deployment and reductions in technology cost. This paper explores this claim for cadmium telluride (CdTe) and copper indium gallium (di)selenide (CIGS) TF technologies and their potentially constraining materials, tellurium and indium. It reviews key literature, highlighting the high uncertainty in the estimates of the resource constrained TF PV potential as well as in data and methodologies used to assess future availability of the targeted materials. The reviewed evidence does not support the contention that the availability of tellurium and indium will necessarily constrain CdTe and CIGS technologies respectively in their ability to supply expected future PV market growth. However, future escalation in indium and tellurium price resulting from demand–supply imbalances could have a negative impact on CdTe and CIGS cost reduction ambitions. Factors influencing indium and tellurium price and their relative contribution to TF PV module production cost need further investigation.

Contents

1. Introduction

The global market for photovoltaics (PV) has experienced an unprecedented growth in the past decade, mainly driven by renewable deployment targets and government incentives such as feed in tariffs. Global production of PV modules grew from 202 MW in 1999 to above 10GW in 2009 [1,2]. Strong market growth is widely expected to continue and some scenarios anticipate that PV generation will play a major role in the future global energy mix (up to 11% of global electricity by 2050 [3]). A variety of PV technologies are available or under development. They can be grouped in several ways but a commonly used categorisation divides them in three generations: crystalline silicon (c-Si) technologies (1st generation) are mature and reliable technologies currently dominating the PV market (about 82% of global cell production in 2009 [1,4]); inorganic thin film (TF) (2nd generation) are currently the main alternative to c-Si and have recently gained market share (accounting for about 17% of the global cell production in 2009 [1,4]); 3rd generation technologies include a wide variety of technological approaches mostly at the research stage and relatively far from commercialization.

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PV electricity generation costs currently ranges between 0.24 and $0.72/kWh, according to the system type and the solar irradiation. Such costs are expected to go down to the $0.13–0.31/kWh range, which would imply grid parity[1] could be achieved in high irradiation countries [3]. Despite dramatic progress in reducing PV module prices (reducing from about $70/Wp in 1976 to around $2/Wp (€1.7/Wp[2]) in 2008 [1,5] further PV module cost reductions are needed to achieve such PV generation cost goals. Among currently commercialized technologies TF PV seems to have a major potential for cost reductions, provided that the expected increase in production facility sizes and improvements in efficiencies are realised [6–8]. Cadmium telluride (CdTe) thin film module is currently the least expensive to manufacture, with module production cost of $0.76/Wp [9] and further cost reduction are believed to be achievable for all thin film technologies, down to the $0.3–0.5/Wp range [6–8].

However, the relative scarcity of some key component materials, and their resultant high price in the future, has been recently and increasingly highlighted as a potential barrier to further market expansion and reduction in cost. In particular, major concerns have been raised for indium and tellurium availability and potential risks for the TF PV technologies that utilize them, i.e. cadmium telluride (CdTe) and copper indium gallium (di)selenide (CIGS). Indium and tellurium prices have increased dramatically in recent years with indium jumping from $320/Kg to $800/Kg in 2004 and tellurium from $71/Kg to $303/Kg in 2005 [10]. This has spurred concerns about their impact on CdTe and CIGS module costs. The potential impact of materials scarcity and price increases on future development of TF technologies is not well understood. Is the market expansion of CdTe and CIGS TF PV technologies going to be physically constrained by the amount of indium and tellurium available globally? Will the cost reduction in thin film devices be undermined by high materials prices? With the aim of assessing the relative weight of such concerns and answering some of the above questions, the paper critically analyses the existing evidence base on indium and tellurium resources and considers the implications for future TF PV technology development and deployment. It also points out the importance of looking at the drivers behind materials price formation and the potential materials price pressure on module production costs.

Section 2 reviews the existing literature on materials availability for PV. The variety of assumptions and methodologies used as well as the high degree of uncertainty in the available estimates of CdTe and CIGS PV technologies future development potential are highlighted. Section 3 identifies gaps in data sources and methodologies used in the above literature for the assessment of indium and tellurium resources. Section 4 draws some conclusions by comparing literature estimates of indium and tellurium constrained CdTe and CIGS future expansion with future PV sector growth scenarios. Section 5 discusses the importance of considering indium and tellurium price trends implications for TF PV technologies and looks into the major drivers behind the materials demand–supply market dynamics.

2. Materials for TF PV technologies: literature contributions and uncertainties

Since the late 1990s an increasing body of academic literature has been exploring material availability issues for large scale PV production [11–17]. These contributions generally look at a range of PV technologies, spanning from c-Si and TF PV to some of the 3rd generation technologies. They also vary in terms of range of materials investigated with some focusing on the main component materials currently used in PV technologies and others looking at a wider range of materials [11,13,14], including possible substitute materials [12,15,16]. Systematic evaluation of the literature suggests that, despite the differences in the approaches taken (as discussed below), potential scarcity of indium and tellurium is often identified as posing a potential risk to TF PV deployment, and to CdTe and CIGS TF PV in particular.

Table 1 summarises some of the main contributions in the literature looking at the impact of materials scarcity on PV technologies, focusing on their assumptions and results applying to CdTe and CIGS technologies. The list is not intended to be exhaustive, but it provides a good picture of the major contributions in the field and the evolution of the literature over the last decade. The studies considered vary considerably in terms the assumptions used in assessing the impact of potential indium and tellurium scarcity on CdTe and CIGS future expansion. They assume different figures for cell efficiency, thickness of the semiconductor layers and material utilization (i.e. the fraction of feedstock material actually ending up in working solar cells), which all affect materials usage per Wp of cells produced. The data and methodologies used to assess future availability of indium and tellurium also vary considerably among the studies (as further discussed in Section 3). They also take differing assumptions in terms of materials recycling (see also Section 3) and in terms of share of the global material resource supply allocated to the PV industry. In addition, the potential future expansion of CdTe and CIGS technologies is estimated using different methods and units of measurement. The various methods fall into two groups:

1. Estimates of maximum *annual production* achievable by a given PV technology, i.e. the maximum annual market growth potential. As such it is measured in GWp per year.
2. Estimates of the maximum level of PV technology deployment achievable. This can be measured as: (a) the maximum *cumulative installed capacity*, measured in GWp; (b) the maximum *annual electricity generation* from PV, measured in TWh[3] per year.

Table 1 shows how the differences in assumptions and methods translate into wide ranging estimates of the impact of indium and tellurium supply constraints on potential expansion of CdTe and CIGS TF PV, as well as in different authors' conclusions in terms of implications for their future development.

Estimates of maximum annual production achievable range from 20 GWp/yr to 211 GWp/yr for CdTe and from 17 GWp/yr to 152 GWp/yr for CIGS. Similarly, maximum installed capacity estimates ranges from 120 GWp to about 11,000 GWp for both CdTe and CIGS. Such wide ranging results make quantification of the impact of potential indium and tellurium scarcity on CdTe and CIGS technologies quite uncertain. In fact, some studies are more concerned about the impacts of indium constraints [12,14], others consider tellurium constraints to be more significant [11,15,16]. It is also important to note that recent studies [14,16] are becoming less pessimistic about future availability of indium and tellurium, possibly as a result of more sophisticated methods and of increasing knowledge and data collection for indium and tellurium over the past decade. They suggest that the implications of rising material costs as a result of relative scarcity may be more significant to the future development of CdTe and CIGS technologies than any

[1] PV grid-parity is defined as the intersection of levelised cost of electricity of PV and local electricity price in time.

[2] Currency conversion is based on 2009 OECD Purchasing Power Prices for Euro area of 0.859€/$.

[3] Note that these two measures could easily be compared assuming a figure for average worldwide PV performance, as done in Table 1 for Wadia et al. [16].

Table 1
Summary of methods, assumptions and results in the literature.

Paper	Method and results[a]	Assumptions	Main conclusions
Andersson et al. [12]	In and Te requirement to 100,000 TWh PV generation exceeds reserves by a factor of 650 for In and 110 for Te	*Efficiency*: 10% (both CdTe and CIGS) *Layer thickness*: 1.5 μm CdTe; 2 μm CIGS *Material utilization*: 100% (no process losses) *Amount of material available for PV sector*: 100% *Recycling*: NA	Indium most critical material, followed by tellurium
Andersson [11]	*Annual production* (by 2020): 20 GWp/yr CdTe; 70 GWp/yr CIGS	*Efficiency*: 12% for CdTe and 14% for CIGS *Layer thickness*: 1 μm Cdte; 0.5 μm CIGS	CdTe more constrained than CIGS
	Cumulative installed capacity[f]: 300 GWp CdTe; 90 GWp CIGS[b]	*Material utilization*: 100% (no process losses) *Amount of material available for PV sector*: 100% *Recycling*: 100%	
Keshner and Arya [15]	*Annual production*[f]: 29 GWp/yr CdTe; 676[c] GWp/yr CIGS	*Efficiency*: NA *Layer thickness*: 1.8 μm Cdte; 2 μm CIGS *Material utilization*: 75% *Amount of material available for PV sector*: NA *Recycling*: NA	CdTe more constrained than CIGS
Feltrin and Freundlich [13]	*Cumulative installed capacity*[f]: 120 GWp CdTe; 120 GWp CIGS	*Efficiency*: best lab efficiencies in 2008 (>10%) *Layer thickness*: NA *Material utilization*: 100% (no process recycling losses) *Amount of material available for PV sector*: 25% (including secondary material) *Recycling*: Implicit in availability assumption above	CdTe and CIGS severely constrained
Fthenakis [14]	*Annual production* (by 2075): 20–211 GWp/yr CdTe; 17–152 GWp/yr CIGS[d]	*Efficiency*: 13–14% for CdTe and 14–16.3% for CIGS *Layer thickness*: up to 1 μm for Cdte; 0.8 μm for CIGS *Material utilization*: 90% for CIGS; NA for CdTe *Amount of material available for PV sector:* 50% of growth for In; total minus 322t/y for Te *Recycling*: 90%	In and Te availability not an issue Potential price increase can be an issue
Wadia et al. [16]	*Cumulative installed capacity*[f]: ∼11,000 GWp for both CdTe and CIGS[e]	*Efficiency*: maximum theoretical limit *Layer thickness*: NA *Material utilization*: NA *Amount of material available for PV sector*: 100% *Recycling*: NA	In and Te availability not an issue. Tellurium more constrained than In Potential price increase (due to high extraction cost) can be an issue

[a] Only upper range results' figures are here presented.
[b] Assumptions used for this estimates are more pessimistic than those presented in third column. In particular efficiencies are set to 10% and layer thickness to 2 μm for both CdTe and CIGS.
[c] Under authors assumptions Se availability becomes a constraint to CIGS at 65 GWp.
[d] The author also estimates maximum annual production in 2020 and 2050.
[e] In and Te reserves enough for CdTe and CIGS to generate about 17,000 TWh. Assumed average worldwide PV performance of 1450 kWh/kWp.
[f] No time frame is provided for these estimates.

fundamental limit on material supply. We return to the interaction between demand, supply and price in Section 5.

3. Comments on assessment of materials availability

A robust assessment of the materials' constrained potential of a given technology should be based on equally robust estimates of future availability of those materials. However, the estimates of future availability of indium and tellurium used in the literature present several uncertainties, both in the data and in the methodologies adopted. Table 2 summarises data sources and methods used in the studies considered in the previous section.

3.1. Data sources for indium and tellurium availability

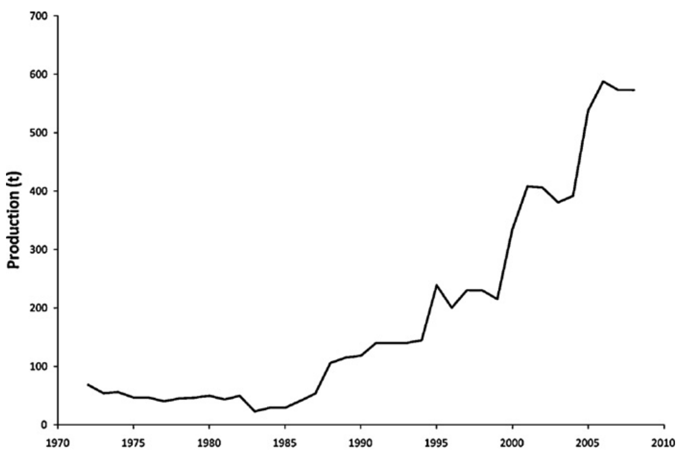
As Table 2 shows, all but one of the studies rely on the same source of minerals data: the US Geological Survey (USGS)[4] which

[4] The other major resource for minerals data quoted in the literature [11] is the Minerals Handbook [18]. However, unlike the USGS data, the Minerals Handbook is not published annually, and has not been published in recent years, limiting its use. It is also harder to access than the freely available USGS data. Several other sources of specific data can be found in literature and authors such as Harrower [19] are used to meet specific data not provided by the USGS (see Table 2).

Table 2
Summary of indium and tellurium data and assumptions in literature.

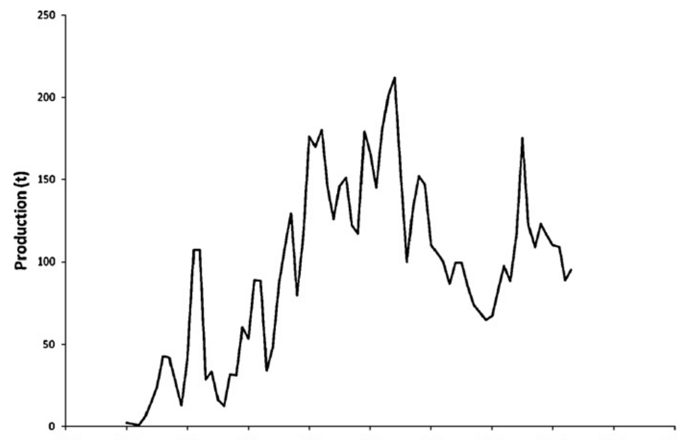
Paper	Data	Assumed indium availability (tonnes)	Assumed tellurium availability (tonnes)
Andersson et al. [12]	Crowson (1992)	*Cumulative*: 2153	*Cumulative*: 21,818
Andersson [11]	USGS MCS (1998); Harrower (1998); Crowson (1994)	*Annual*: 290 *Cumulative*: 2,600	*Annual*: 290 *Cumulative*: 20,000
Keshner and Arya [15]	USGS MCS (2004)	*Annual*: 26,143[a]	*Annual* 2000[a]
Feltrin and Freundlich [13]	USGS MCS (2005)	*Cumulative*: 625[b]	*Cumulative*: 5250[b]
Fthenakis [14]	Green (2006); Ojebuoboh (2008); Menzie (2006); Kapur (2005); Ayres et al. (2002); Tilton et al. (2007); Gordon et al. (2006); USGS MY (2006)	*Annual*: 1412[c]	*Annual*: 797[c]
Wadia et al. [16]	USGS MCS (2007)	*Annual*: 588 *Cumulative*: 6000	*Annual*: 128[d] *Cumulative*: 47,000

[a] Authors estimate of potential future production based on crustal abundance.
[b] Figure based on 25% of reported reserves.
[c] Production in 2020 based on a scenario forecast of future material supply to 2075. Does not include recycled metal.
[d] Does not include US production.



Note: World production data were for production of indium for the years 1972–74 and for refined indium for the years 1975 to the most recent. Data for the years 1972 to the most recent do not contain U.S. production.

Fig. 1. Historical world production of indium as reported by the USGS.



Note: World production estimates do not include U.S. production data for the year 1931 and for the years 1976 to 2003 because the U.S. data are proprietary. After 2003, total world production was not available.

Fig. 2. Historical world production of tellurium as reported by the USGS.

publishes a collection of production and reserves data for various important mineral resources in its Minerals Commodity Summaries (MCS) and Minerals Yearbook (MY). It is important, therefore, to discuss the limitations these data may have.

Production volumes of a non-renewable resource are less controversial than reserves data since production volumes are more easily measured [20]. Historical production data for indium and tellurium are in fact available (and presented in Figs. 1 and 2), although the USGS have not presented US or global production figures for tellurium since 2003 to "*. . .avoid disclosing company proprietary data*" [10].

Reserve estimates are less straightforward. USGS gather data from a range of sources including individual countries own assessments, academic articles, company reports, company presentations and trade journals. However, the ideal reserve estimation process ". . .would be comprehensive evaluations that apply the same criteria to deposits in different geographic areas and report the results by country" (USGS). This would require large resource and significant international cooperation, which may be unlikely in the short to medium term. Reserves estimation for indium and tellurium in particular is further complicated by the 'secondary' nature of the materials, as both are recovered as a by-product of mining and refining of other metals. Tellurium is commonly associated with the recovery of copper, but is also a component of other refining processes including refining of lead. Indium is primarily produced as a by-product of zinc production, though it is also found in iron, lead and copper ores.

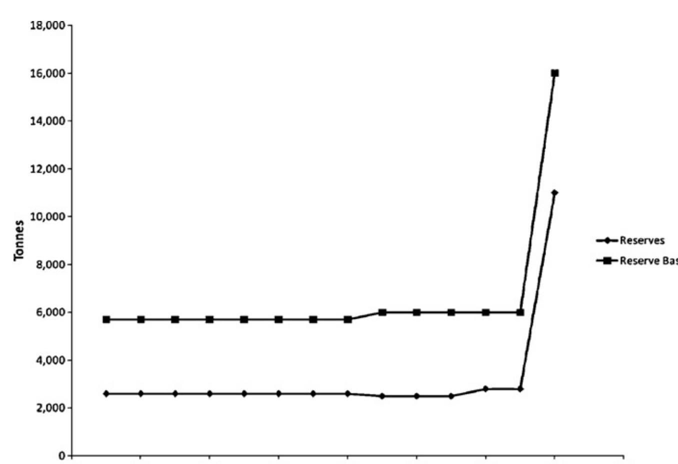


Fig. 3. USGS historical indium reserve and reserve base data.

For indium, USGS reserves figures are based on the indium content of zinc ores only (Fig. 3) and there is no clear agreement on the most recent figures. When last reported USGS estimated indium reserves associated with zinc ores at 11,000 tonnes, but other authors have suggested that indium reserves may be as much as 50,000 tonnes, based on a wider inclusion of resources [21]. Moreover, reserves figures have not been reported by the USGS

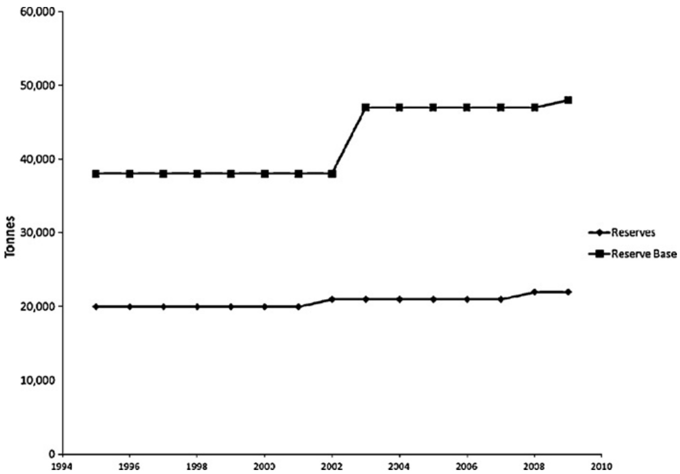
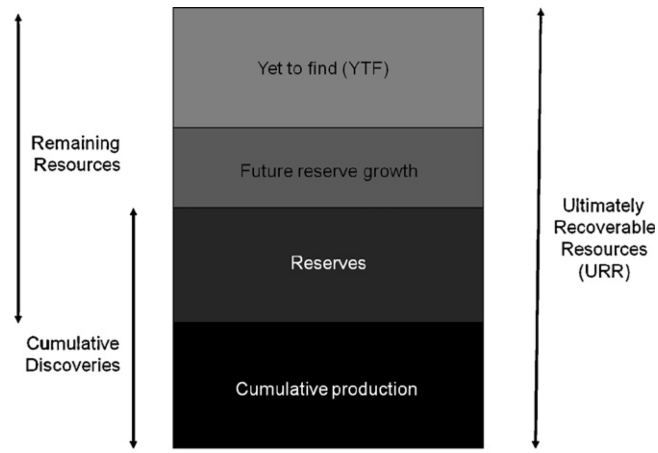


Fig. 4. USGS historical tellurium reserve and reserve base data.



Source: Authors' own

Fig. 5. Components of the ultimately recoverable resource.

since 2008, possibly as a result of the large increases seen in Chinese indium reserve reporting, which account for the dramatic rise in world reserve figures seen in Fig. 3.

For tellurium only those resources which are associated with copper mining are included in reserve estimates (Fig. 4). Though these resources have the highest probability of being produced, other resources do exist, including two mines in China listed as 'primary tellurium' mines, and smaller deposits associated with zinc and silver mines [22,23]. These marginal reserves may indicate the potential for reserve figures to be increased in the future.

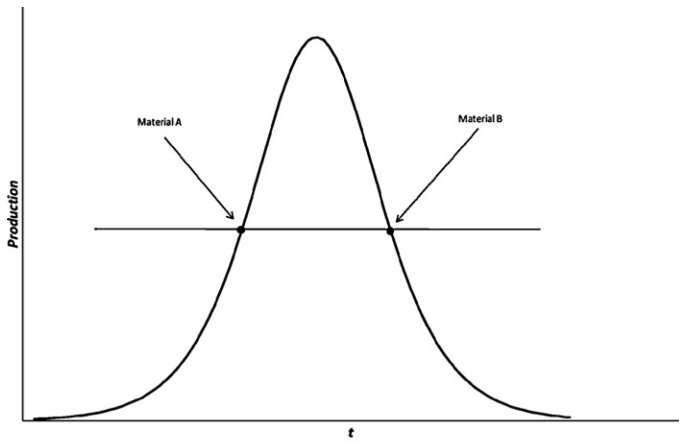
The reserves reported by the USGS are defined as "*...that part of the reserve base which could be economically extracted or produced at the time of determination*". This can be described as a conservative definition, and typically estimates of this type are exceeded over time for many exhaustible resource types. Until 2009 the USGS also published data on 'reserve base', defined as "*...the in-place demonstrated (measured plus indicated) resource from which reserves are estimated. The reserve base includes those resources that are currently economic (reserves), marginally economic (marginal reserves), and some of those that are currently subeconomic (subeconomic resources)*". This practice was discontinued for the 2010 edition due to lack of up to date assessment of reserve base, a function previously provided by the now defunct US Bureau of Mines. However, it is also important to acknowledge that as economics change over time, so too does the estimate of reserves. By implication, as the resource reaches supply limitations the price will increase and marginal reserves will become available. The estimated reserve is also likely to increase over time as geological knowledge of deposits improves: financial reporting practices tend to encourage conservative reserve booking before geological knowledge improves. A third way that the estimate of reserves may change over time is through improvements in technology. As the price of a scarce resource increases, the development and application of innovative recovery techniques is incentivised, improving recovery rates and helping to access marginal deposits. These three factors (marginal reserves, improving geological knowledge and technological advance) are collectively referred to as 'reserve growth'. The reserve is also likely to change over time as new discoveries are made. The potential for this depends on the cumulative discovery effort but estimates of 'yet to find' (YTF) resources are common in other resource assessment [24]. Reserves, reserve growth, and YTF can be collectively referred to as Ultimately Recoverable Resources (URR) (Fig. 5). This concept of resources is more common to assessments of oil resources, but can equally be applied to other non-renewable resources such as tellurium or indium.

In order to have a comprehensive assessment of the future potential of mineral supply an assessment of URR is needed. This is not always straightforward, however, and conducting such an assessment can involve significant time and resource. To conduct such an assessment for either indium or tellurium would also involve assessments of the future recovery of their associated metals, typically zinc or copper (but this would also have to include any marginal resources associated with other primary metal ores), and an assessment of any changes in recovery rates and concentrations of secondary metal over time. The estimation of YTF for each of these materials, however, is likely to be more resource intensive, and will ultimately be subject to greater uncertainties.

Altogether the issues discussed above lead to the conclusion that the availability and quality of data on indium and tellurium production and reserves is not entirely suited to the estimation of future supply trajectories. This data issue is common among mineral resources and has similarly limited other resource supply forecasting efforts [25].

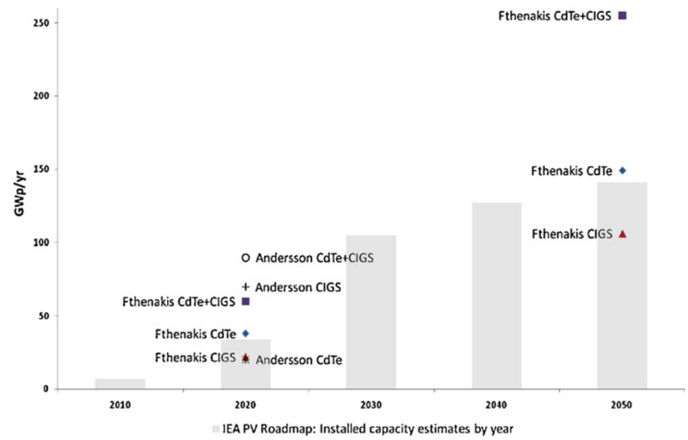
3.2. Literature assumptions and methods

These data issues and uncertainties are reflected in the variety of assumptions and methods used in the literature here examined for indium and tellurium availability estimation (as shown in Table 2). In the simplest examples authors use current mineral production figures as a metric for future availability [11,15,16], and the access to and reliability of current mineral production data may encourage this approach. In these examples, current production is used as a proxy for future *annual* production potential, or as a relative indicator to be measured against future annual demand. However, while historical production is a valuable parameter in any assessment of future supply, current production alone is unlikely to be an accurate predictor of future material availability. It has long been understood that the production of a finite resource will necessarily take the form of a curve, starting and finishing at zero, with one or several maxima between these two points (Fig. 6) [26]. Though tellurium and indium production is constrained by the production of their associated primary metals, these primary metals will likely conform to such a production curve. It is clear therefore that production of indium and tellurium will not remain at current levels indefinitely. In addition, to use current production as a form of reference to compare between different materials can be misleading. Two materials with exactly the same current production, and the same demand forecast may have entirely different future supply prospects (Fig. 6). A material at the beginning



Source: Authors' own

Fig. 6. Generic production cycle for two exhaustible materials.



Source: Authors' own, based on [3, 11, 27]

Fig. 7. Most pessimistic and more optimistic estimates of material constrained annual production against IEA forecasts of future PV market size (GWp/yr).

of its production curve (Material A) may have a much greater future production potential than one toward the end of its production cycle (Material B), regardless of current production figures. Moreover, the shape of the production curve represents the geological, economic and geopolitical constraints on the extraction of the recoverable resource. These constraints vary and affect the rate at which reserves of a specific metal can be extracted. Of the literature in Table 2 only Fthenakis assumes a production profile for the future supply of indium and tellurium [14].

More typically, material constraint assessments in the literature involve some form of reserve estimate [11–14,16]. In these examples, reserve estimates are either used as a proxy for future *cumulative* production, or to inform estimates of future production. Reserve estimates can and should be used to inform a more realistic projection of future material supply than current production. However, while reserve data may provide a better basis for future availability estimates it is important to acknowledge both the economic and time dependent nature of reserve estimates and the geological restrictions on the accessibility of these reserves, as discussed above. Among the studies presented only Fthenakis [14] estimates a future production profile for both indium and tellurium. This is achieved by examining estimates by other authors of future production profiles of associated primary metals (copper in the case of tellurium, and zinc in the case of indium) and applying estimates of recoverable secondary metal based again on the literature on tellurium and indium recovery rates. This involves a diffuse academic literature which examines different areas of the material supply process, including primary metal supply scenarios, secondary metal concentrations, and secondary metal recovery rates [27,28].

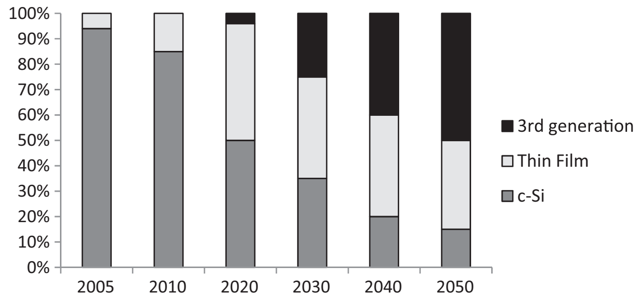
It should also be pointed out that that recycled indium and tellurium are not fully accounted for by the literature in estimating materials' future availability. Many of the material constraints estimates in current literature use time horizons of several decades. Over this time period end-of-life products containing indium or tellurium could represent a significant source of those metals. Recycling of indium and tellurium from several end uses is feasible and very high recovery rates have been reported. Indium is increasingly reclaimed from deposition process of indium tin oxide (ITO) in liquid crystal displays (LCDs) manufacturing, which accounts for more than 50% of primary indium demand [21,23,29]. Recycling rates of indium from LCD could reach 92% based on existing research [30]. Average recovery rates of around 90–95% are possible for Te from CdTe end-of-life cells [31–34]. Indium recycling from CIGS modules seems less well developed and future recycling rates from end of life CIGS modules is still unclear [33]. Furthermore, the anticipated increase in price associated with scarcity could incentivise the recovery of metals from this in-use source. Only three of the studies presented in Tables 1 and 2 make any explicit assumption regarding end-of-life recycling, of which one demonstrate full acknowledgement of the recycled material in supply forecasts for indium and tellurium [14] and two of these present simplistic assumptions [11,13]. More can be done to develop these estimates in a more robust way in order to provide a more comprehensive estimate of materials availability for future TF PV technology manufacturing.

In summary, while the available data may lack a certain level of accuracy, still more can be done to improve the sophistication of availability estimation methodologies to improve the robustness of results. Simple estimations which utilize production or reserve figures directly may provide useful metrics which explore the magnitude of the future supply challenge. However, priority should be given to the development of future materials production scenarios which address a range of assumptions regarding the temporal nature of resource economics, reserve estimation, and recovery rates.

4. Implications for CdTe and CIGS future developments

The previous sections have highlighted how quantification of the impact of potential indium and tellurium scarcity on CdTe and CIGS technologies is quite uncertain. Available estimates depend on varying assumptions and data, and methods used for the assessment of future indium and tellurium availability are diverse and not entirely suited to the estimation of future supply trajectories. Nonetheless, some considerations on potential indium and tellurium constraints to future CdTe and CIGS developments can be made.

Fig. 7 compares the most pessimistic [11] and more optimistic [14] estimates of maximum annual production presented in Table 1 to recent IEA forecasts of future PV market size [3]. In a world where either CdTe or CIGS exists exclusively, materials constraints may impact the ability of either to satisfy future market growth alone (although the two studies reach opposite conclusions, with Fthenakis estimating lower potential for CIGS than CdTe in 2020 and Andersson estimating the opposite). However, if parallel deployment of the two TF PV technologies is considered the materials constrained total 'Cdte + CIGS' annual production capacity is more than sufficient to satisfy IEA estimated market size. In other words, future indium and tellurium availability is enough to guarantee annual production of CdTe and CIGS well beyond forecast future PV market expansion.



Source: Author's own, adapted from [37]

Fig. 8. Shifts in PV technologies market share over time.



Source: Author's elaboration based on [10]

Fig. 9. Indium and tellurium prices (1994–2010).

Moreover, given the tendency to assume no technological coexistence in the literature presented in Table 1, their conclusions may be considered as 'worst-case' in terms of material constraint to the PV market as a whole. Indeed, materials constrained potential of CdTe and CIGS technologies has to be assessed while acknowledging that future market size and cumulative installed capacity are to be satisfied by a mix of PV technologies. TF PV technologies are currently competing with the incumbent crystalline silicon technologies, expected to account for a large market share over the next decade. At the same time novel 3rd generation technologies will make their way toward commercialization. A technology shift scenario – from 1st to 2nd and to 3rd generation technology – is envisaged by several recent PV sector roadmaps [3,6–8,35] and depicted in Fig. 8.

Optimistic industry estimates see TF PV (CdTe and CIGS included) accounting for about 30% of the PV market by 2020 [37]. This translates to only 10.2 GWp/yr of the total IEA PV market size in 2020, a market share that could be satisfied by either CIGS or CdTe alone, based on the most pessimistic estimates presented in Table 1. In addition, technological progress and innovation can help in improving materials availability as well as efficiency in materials utilizations along the materials and TF PV technologies respective value chains. Indeed, materials recovery and extraction rates as well as recycling potential can increase, as already discussed in Section 3. Technological progress can also reduce usage per Wp of indium and tellurium in CdTe and CIGS modules. This can be achieved through several routes:

- Increasing cells and module efficiencies, implying lower materials utilization per Wp. CdTe and CIGS efficiencies have been steadily increasing over the last decade with current highest laboratory cell efficiencies of 16.7% and19.6%, respectively [38]. The highest commercial module efficiencies are of 10.4% for CdTe and 11.2% for CIGS [39], but further potential lays in bridging the gap between laboratory and manufacturing efficiencies.
- Reducing absorber layer thickness (while maintaining efficiency) implies lower materials requirements. Currently CIGS and CdTe absorber layer thicknesses are around 2 μm and in the 3–8 μm range respectively, but research is underway to reduce thickness to below 1 μm [14,40–42].
- Higher material utilization during module production improves usage per Wp. Higher utilization rates can be achieved by reducing wastage and increasing material recycling, during the deposition process. Currently, utilization rates for most common CIGS deposition processes is relatively low (around 34–50%[14,15,43]), but could potentially be increased to 90% through improvements and/or innovative deposition techniques as well as improved utilization of material deposited on the shields of the deposition chamber [14,43]. Utilization rates for CdTe deposition could also increase above current 75% through the same factors [15,44].

Thus, it is possible to conclude that absolute availability of indium and tellurium is not a constraint to future development and deployment of CIGS and CdTe PV technologies *per se*. However, as some contributions in the literature have suggested [14,16], it is the price of indium and tellurium that could have a negative impact on cost reduction ambitions and future developments of CdTe and CIGS technologies. In other words, though future PV deployment and availability of component materials can be discussed in absolute terms, these factors are in fact more subtly dependent on the economics of the PV market and of the wider materials supply chains. The existing literature here considered do not fully acknowledge and assess the conditions affecting demand and supply trends for indium and tellurium, the resulting prices and the relative possible impact on the development of CdTe and CIGS PV technologies.

5. Indium and tellurium market dynamics and prices

Alternating periods of excess demand and over-supply, resulting in market imbalances and price variations, are common in commodities markets. Indium and tellurium historical price curves presented in Fig. 9 show a dramatic jump in mid 2000s. These unprecedented price highs have spurred increasing concerns over future developments of CdTe and CIGS technologies and their cost reduction potential. To which extent future price trends for indium and tellurium can have an adverse impact on such cost reduction ambitions is still unclear and open to discussion. A better understanding of major drivers behind indium and tellurium supply-demand dynamics is therefore crucial to be able to make any further considerations in this respect.

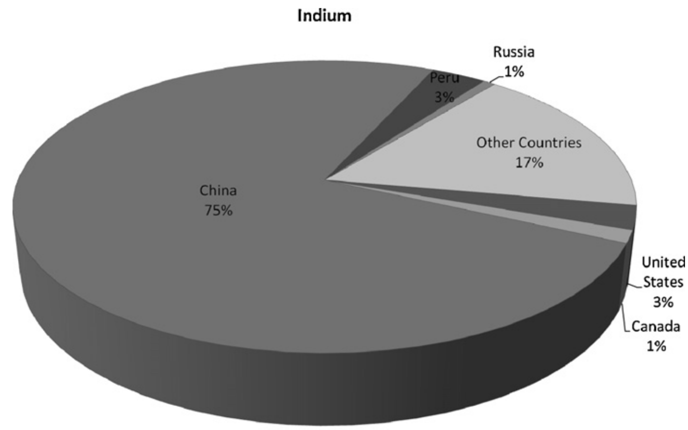
Economic growth is one of the major drivers behind materials demand, price increases and potential scarcity. Recent contributions [45–46] have pointed out that rapid economic growth in developing countries, China in particular, has led to increases in demand for raw materials and relative prices, only partially eased more recently as a consequence of the global financial crisis. However, demand for more specialist materials such as indium and tellurium is rather more likely to be affected by specific technological development and market dynamics of products and technologies relying on them. Indeed, the market for these metals has established demand from specific end-uses.

Beside PV applications, indium is used to produce indium tin oxide (ITO), a transparent conductive layer used in LCD screens, and also used in alloys, as a lead substitute in solders, in light emitting diodes and other electrical uses [47]. The introduction in the market of LCD screens has been one of the major drivers behind the recent years dramatic indium demand. Currently, more than 50% of globally refined indium is used to produce ITOs, in contrast

with PV manufacturing accounting for less than 2% of total indium demand [10,48]. Indeed, the sudden price increase experienced by indium in 2003 and 2004 (see Fig. 9) has been attributed to a substantial growth in demand for ITO, especially in Japan and Republic of Korea, as well as to demand increase for low-melting-point indium (used in some electrical and optical uses) in China [10]. The PV sector accounts for a slightly larger share of the tellurium market, and appears to have had a much more significant impact on prices. PV usage currently accounts for around 11% of total worldwide consumption in 2009 [47,48]. Since 2004–2005 tellurium prices have been increasing dramatically, mainly due to increased demand from PV cell manufacturers and increased demand from China for its main end uses described below (see Fig. 9). Moreover, in 2008 tellurium price experienced an all time high due to speculation that increased investments in CdTe production would have created a tellurium shortage [47]. The leading use for tellurium was as a metallurgical alloying element, with consumption in chemical, catalysts, and other uses, accounting for the next largest end-use category. Other, non-PV electrical uses include thermal imaging technologies and thermoelectric cooling devices. Due to high prices, many steel and nonferrous metals producers have reduced consumption and found substitutes, and tellurium use is decreasing in many of its application [47].

On the supply side, responding to unanticipated escalating price can be complicated by the lead-times involved in bringing on new production. This is compounded by the secondary nature of tellurium and indium production. Since they are co-produced with other metals supply may be relatively insensitive to fluctuations in the price of the secondary metal. However, the indium supply chain has been recently supported by strong demand for ITO, resulting in steadily increasing production and global refining capacity (see also Fig. 1). Moreover, an increasing amount of indium is reclaimed from used ITO targets [29] (Mikolajczak estimates it as being almost twice the amount of total virgin indium consumed [21]) and recovery of indium from processing wastes (tailings and slags) could become a significant source of supply if a sustained demand and price would justify the investment [21,23]. In the case of tellurium, its high price may be counterbalanced by a stable or decreasing price of copper, its co-produced metal. Improvements in the recovery of tellurium from copper anode slimes can go some way to increasing tellurium production, but this has limited impact and may need a significantly higher tellurium price, creating a lag between increasing demand and corresponding supply response. Moreover, a relatively small amount of tellurium is currently recovered from end of life products [23], despite end-of-life recycling of CdTe has been put in place by major CdTe manufacturers and high recycling rates are achievable [33,34]. In addition, some have suggested that given the perceived sustained future demand for indium from LCD screen market, indium suppliers may be more inclined to invest in production capacity than tellurium suppliers. Although PV demand for tellurium is expected to keep increasing, the use of the material is decreasing in many of its historical applications. This makes future demand less certain and suppliers may not see production capacity as an attractive investment [48].

Geopolitical issues may also present a barrier to supply increases for certain materials. Often, natural resource supply can be affected by political instability in the countries of production [49]. Furthermore, these emerging materials markets may also adopt industrial development strategies which actively hamper global markets by adopting export taxes, quotas, subsidies and other protectionist mechanisms [46,49]. Figs. 10 and 11 present the endowment of reserves by country for indium and tellurium. In the case of tellurium, a large proportion of the reserves recorded by the USGS exist in Peru and the United States. These countries are unlikely to provide a significant geopolitical barrier to global tellurium markets. In the case of indium however, concerns have been raised regarding the extent to which China could influence the global market through export quotas. In the second half of 2010, exports of indium were significantly reduced in comparison to exports in the first half of the year [50]. This decision is largely in line with China's decisions on the exports of other important resources such as rare earth metals, generating some concern in the international markets.

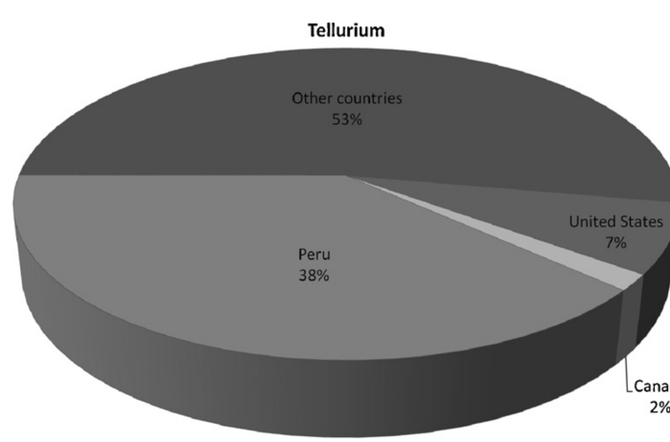


Source: USGS 2008 [53]

Fig. 10. Endowment of indium reserves by country.

In conclusion, an expected growing demand for indium, particularly for ITO production, might result in upward pressure on price, particularly when demand increases are not anticipated by a supply response. On the other hand historical production curves show indium production growing steadily over the last couple of decades (Fig. 1) and the indium supply chain is likely to be supported by a sustained future demand from the LCD screen market as well as by promising recycling practices. However, global indium reserves are comparatively more prone to geopolitics and foreign industrial strategies which may result in upward pressure on prices. Tellurium future demand trends are less clear. Despite expected demand growth the PV market accounts for only a limited share of the global tellurium consumption and demand has recently decreased for many of its other uses. This could result in lower global demand which would ease upward pressure on tellurium prices. However, it might also induce a slower supply response to increasing demand from novel end uses such as CdTe technologies.

The relative impact on prices of such demand and supply forces is unclear. Indeed, as for other commodities, future market



Source: USGS 2010 [10]
Note: Other countries include Australia, Belgium, China, Germany, Kazakhstan, the Philippines, and Russia

Fig. 11. Endowment of tellurium reserves by country.

dynamics and price trends of indium and tellurium are not straightforward to predict. In particular, they cannot be easily estimated on the basis of past time series, as their future evolution is dependent on rather complex supply and demand dynamics of both the raw materials and the end use markets [52]. Thus, the initial evidence presented above should be interpreted with caution and the development of robust and informed price scenarios for those materials should be the focus of any future work in the area.

6. Conclusions

Ambitious goals for renewable energy and generous support regimes in many countries, combined with ongoing technological progress have resulted in rapid expansion of the global market for PV and considerable reductions in the costs of PV modules. TF PV technologies have the potential to provide cost reductions, and CdTe modules are already the least expensive to manufacture. This paper explores the possibility that TF PV technologies, CdTe and CIGS in particular, may be constrained by the availability of key materials, hampering their growth potential and their ability to sustain cost reduction trends in the future.

The existing literature on material availability for PV technologies reviewed in this paper has revealed a great deal of variation in assumptions and methods used, which translate into wide ranging estimates of the impact of indium and tellurium potential scarcity on CdTe and CIGS technologies. The data and methodologies used to assess future availability of indium and tellurium also varies. Use of current production as an indicator of future production has limitations. Data on reserves may provide a more powerful indicator of future production potential, though it is important to understand the long term variability in reserve figures, and the difference between generally conservative estimates of economically recoverable reserves, and more inclusive estimates of the ultimately recoverable resource. Moreover, lack of factoring into the estimates the potential for and contribution of recycling to future material supply may result in future supply underestimations. A better and more structured understanding of future recycling potential is therefore an area which warrants future study. In general, studies which treat future supply as a dynamic system provide better evidence than those studies which treat available resources as a static system.

Notwithstanding the above uncertainties, the evidence reviewed here does not support the contention that the availability of tellurium and indium will necessarily constrain CdTe and CIGS technologies respectively in their ability to supply expected future PV market growth. Furthermore, availability of these materials need not constrain the PV sector in contributing to the goal of decarbonising the global economy. On comparison with common scenarios of future PV deployment, the evidence of existing PV resource availability assessments suggests that CdTe and CIGS technologies are likely to be constrained by indium and tellurium scarcity only under very conservative (and possibly unrealistic) assumptions regarding the available technology mix. If we assume that either CdTe or CIGS is only available between now and 2050, resource constraints may be encountered, inhibiting their ability to satisfy future market growth. And it is important to note that the literature disagrees as to which technology (CIGS or CdTe) is most likely to precipitate such a constraint. However, when a more realistic scenario of PV technologies future coexistence is considered, this resource constraint becomes unlikely. We have not examined the potential materials constrained contribution of 1st and 3rd generation PV technologies here, but assuming that their contribution is greater than zero further decreases the likelihood of a resource constraint to TF PV between now and 2050.

Nonetheless, future escalation in indium and tellurium price resulting from demand–supply imbalances could have a negative impact on CdTe and CIGS cost reduction ambitions and hence hinder their future expansion. Explicit analysis of price effects of materials' demand and supply dynamics are not covered in the literature reviewed in this paper. This area, however, might have a significant impact on the future of the TF PV technologies here considered. Some of the complexities and drivers behind demand, supply and price formation for indium and tellurium have been highlighted. The need for more robust and informed price scenarios for those materials is also expressed. Indeed, a better understanding of future scenarios for TF PV sector demand of indium and tellurium and conditions affecting their usage in CdTe and CIGS technologies (including the role and impact of technological innovation) is needed. Possible future growth of competing end-uses should also be explored and accounted for in the analysis. On the other hand, the materials supply chains should be better analysed to inform future scenarios for supply response and to further explore recycling potential (both from end-of-use products and within the value chain). It is also not fully clear how sensitive CdTe and CIGS manufacturing costs might be to fluctuations in prices of indium and tellurium and to which extent innovation and technological progress might reduce materials usage and ease impact of future supply constraint and price increases. Indium and tellurium prices may be fundamental to the cost effectiveness and successful deployment of TF PV. More work is needed to quantify their relative contribution and relationship to overall total TF PV module production cost.

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